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III. GEOSPATIAL TECHNOLOGIES AND INNOVATIONS IN GEODESY, REMOTE SENSING, AND ENVIRONMENTAL MONITORING

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NEW POSSIBILITIES FOR DOCUMENTING HISTORICAL UNDERGROUND SPACES USING HANDHELD LASER MOBILE SCANNERS AND MODERN VISUALIZATION OF ACQUIRED DATA

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Abstract. Recently, there has been a significant increase in interest in historical mining sites as cultural monuments. For a long time, historical mining sites were neglected as cultural and technical monuments and were not accessible to the public. This article focuses primarily on the documentation, exploration, and accessibility of historical mining sites using modern geomatics technologies. The article deals with the historically rich mining activity in the Czech Republic, where there are several important areas of historical mining from the Middle Ages to modern times. Until recently, it was very difficult to accurately map completely irregular and poorly accessible underground spaces. The only methods that could be used were a miner's compass, a tape measure, a folding ruler, or a laser rangefinder and inclinometer. With the rapid development of handheld laser mobile scanners using SLAM (simultaneous localization and mapping) technology, this task has become much easier; on a smaller scale, low-cost documentation technologies using smartphones, panoramic cameras, and appropriate applications can also be used. It is now possible to document hard-to-reach, dark, and, above all, very irregular and narrow spaces in high quality. Nevertheless, there are many problems that the article points out and analyzes; these include measurement speed, cost, accuracy, and the effects of humidity and lighting. The SLAM method of handheld mobile laser scanners proves to be the most powerful.

Keywords: laser scanning, low-cost devices, mobile laser scanning, mining, historical objects, documentation, TLS, PLS, ALS.

1. Introduction

Historical mining activities have left an indelible mark on the landscape and underground and have been linked to the development of human society since time immemorial. Ore mining was an important part of technological progress. In many cases, these were or are significant technical achievements and ingenious works, but they have been on the margins of interest in terms of monument preservation. This has recently changed, and so-called mining tourism is a sought-after tourist attraction in areas where historical mining took place and where the spaces have been safely adapted and made accessible to visitors.

An essential element of any object is its accurate documentation (Remondino, 2011; Faltýnová et al., 2016; Pavelka & Pacina, 2023; Tumeliene et al., 2017). For buildings, plans and sections are commonly created as technical drawings. In historic mining structures, which are usually completely irregular and follow the ore vein, this type of documentation cannot be easily used (Makkonen et al., 2015). Regarding the classic documentation technology of the last century, when theodolites or later total stations or photogrammetry were used, irregular underground spaces posed a fundamental problem (White, 2016). In narrow, dark, winding, and damp spaces, miners used compasses, tape measures, folding rulers, inclinometers, and later laser rangefinders. This also applied to the documentation of caves, and speleologists commonly used these tools until recently.

The development of new technologies (Jaakkola et al., 2008), particularly the miniaturization of IMU (Inertial Measurement Unit) units and laser heads, has made it possible to construct small, hand-held devices in the form of laser SLAM scanners (Běloch et al., 2025; Di Stefano et al., 2021).

Recently, with the development of chip speed and data storage in smartphones, there has been a sharp increase in low-cost devices, usually in conjunction with a smartphone and an app.

The problems of objects, which are often high humidity, confined spaces, and very slow passage through

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the object, define the possibilities for using documentation devices. In some areas, it is necessary to crawl through low spaces. This can lead to errors such as double objects, incorrect reflections from water surfaces, or incomplete scans due to very short, measured distances.

The aim of the research is to address the issue of documenting historical underground spaces, analyze current data collection and processing options, and define the limits of usability. Everything is being investigated at various locations in historical gold, silver, and tin mines in Jílové u Prahy, Kutná Hora, and Jáchymov.

Professional SLAM scanners GeoSlam Go and Faro Orbis were used for the work, and low-cost systems using smartphones and smart applications were also tested. However, the research does not end with the acquisition of data. Very irregular spaces need to be mapped and visualized. Traditional methods fail here precisely because of the irregularity and spatial diversity of the objects. The method of projection and sections, which is one of the classic technologies, has proven itself, but virtual or augmented reality is proving to be a very suitable method for making objects accessible to the wider public.

Research suggests that modern technology will make it possible to at least partially present some unknown and normally inaccessible objects to the wider public (Pavelka et al., 2023). Proof of this is, for example, the inclusion of the Czech-Saxon Ore Mountains on the UNESCO World Heritage List (https://whc.unesco.org/en/list/1478/).

2. Data and materials

For 10 years, our research has focused on technologies for documenting historical underground spaces associated with ore mining. It is necessary to distinguish between two basic types of mining spaces. a) Open-pit spaces (collapsed mines, surface pits, spoil heaps, dumps, surface mining); b) Underground spaces (shafts or tunnels, underground domes).

For surface-open historical mining features, drones with RGB cameras or lidar, TLS (Terrestrial Laser Scanning) or PLS (Personal Laser Scanning) can be used, depending on their size (GeoMatching, 2026). For classic underground spaces, PLS can be used, with TLS also being a possible option. In recent years, however, low-cost technologies associated with smartphones or panoramic cameras have also become popular.

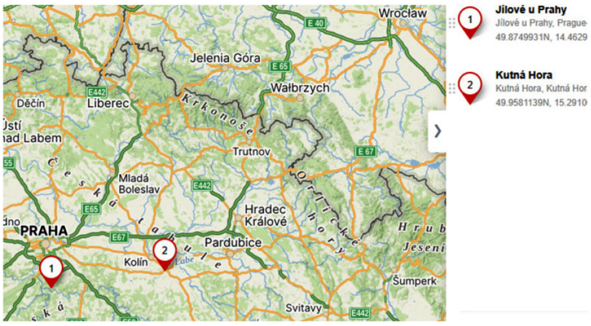
Various documentation projects in the Ore Mountains (open-pit mines, e.g., Wolf pits, Mariánská, East Abertamy, underground mines U Pinců, Jáchymov, Johannes, Kohlreuter near Boží Dar, Mauritius near Hřebečná, all mostly associated with silver and tin mining), as well as the gold mine near Jílové and the silver mines in Kutná Hora) were examined. Each location is different, and various documentation and visualization tools were used.

3. Case projects

On following figures our research activity is shown (Figures 1–2).

1	**Vlčí jámy**	50°23'53.803"N, 12°46'49.035"E 50.3982786N, 12.7802875E
2	**Východní Abertamy**	50°22'27.609"N, 12°50'40.778"E 50.3743358N, 12.8446606E
3	**Mariánská**	50°21'58.983"N, 12°53'49.107"E 50.3663842N, 12.8969742E
4	**U Pinců**	Svojsíkova cesta, Jáchymov, Karlovy Vary 50.3711881N, 12.9126919E
5	**Johannes**	50°25'59.420"N, 12°52'18.187"E 50.4331722N, 12.8717186E
6	**Kohlreuter**	50°26'7.736"N, 12°52'19.963"E 50.4354822N, 12.8722119E
7	**Mauritius**	50°23'14.405"N, 12°49'53.193"E

Figure 1. Projects in Ore Mountains



1	**Jílové u Prahy**	Jílové u Prahy, Prague 49.8749931N, 14.4629
2	**Kutná Hora**	Kutná Hora, Kutná Hor 49.9581139N, 15.2910

Figure 2. Projects in lowland, adits and shafts

3.1. Open-pit mines

Two of the projects in the Ore Mountains can be used as examples of an open space.

The so-called Wolf Pits (Figure 3) are the remains of the Jiří and Wolfgang mines, which are important evidence of the historical mining of greisen tin ore in the Ore Mountains. In both mines, the deposits were mined almost to the surface, and when their weak ceiling collapsed, sinkholes were created. These subsequently expanded further due to the landslides of loose rock from the walls. The Wolf Pit was created by mining the Wolfgang vein. The sinkhole is approximately 120 meters long, up to 14 meters wide in places, and reaches a depth of about 20 meters. The remains of old collapsed corridors and chambers are visible in it. The mine was already in operation in 1532, reaching a depth of 85 meters, and was one of the largest mines in the Hornoblatenský district (Figures 3–6).

This location was flown over by an EBee winged drone (90 images were taken with a Canon IXUS 127 HS camera, 16.5MPix, from a height of 130–220m with up to 80% overlap). The location is on a slope.

Furthermore, TLS Faro Focus 3D X 130 was used with a measurement accuracy of +/−2mm and a range of up to 130m.

The data was processed using Agisoft Metashape software for the don and Scene software for the TLS data. This resulted in two-point clouds, each with certain invisible parts. The logical step was to merge both point clouds into one using common visible points. The clouds were cleaned of vegetation, and the resulting holes were filled in. Geomagic Wrap software was used. Final mesh model has about 120milion triangles after cleaning and reduction (Figures 4–6).

Figure 3. Terrestrial view on the “Wolf Pits”

Figure 4. Used Ebee drone

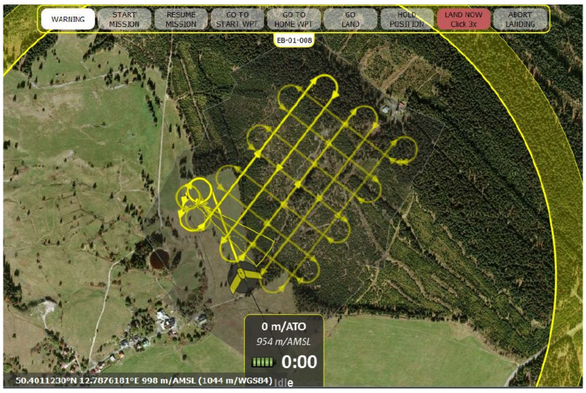


Figure 5. Final flight planned trajectory against the background of an aerial orthophoto (eMotion, image flight plan)

The second test project involved scanning using PLS technology in a wooded area of Východní Abertamy (East-Abertamy)). Here, we found pits from the 16th century tin ore mining era, curiously located right next to a uranium mine from the 1960s. As a prime instrument the GeoSlam Go small handheld laser scanner was used (Figure 7). It has a range of about 40metres and scanning speed 40thousand points per second, without a camera. The precision is 1–3 centimetres on 10 metres, which is enough for this type of projects.

The existing state free 5th generation digital terrain model (DMR5) and low-cost airborne laser scanning (ALS) were also used.

3.2. Shafts and adits

Typical historical tunnels were documented using various means that could be used underground.

Classical SfM-MVS (Structure from Motion and Multi View Stereo) photogrammetry was first used in the Kohlreuter mine at a time when mobile handheld

Figure 6. Used TLS Faro

Figure 7. PLS GeoSlam Go

laser scanners were not available. Analysis has shown that smaller enclosed spaces can be documented, but very good lighting is required. Narrow tunnels cannot be scanned in this way, and photogrammetry cannot be used here. In the past, photogrammetric systems based on light cross-sections existed for larger tunnels and galleries, but these are no longer in use today.

Today, TLS and PLS are probably the most used methods. In our project followed instruments were used: BLK360, it has a range of about 40 m and an accuracy of 4-5 mm at 10 m and includes a camera and a thermal imaging sensor. Faro Orbis – this device has a significantly higher scanning speed of up to 600,000 points per second, a range of up to 60 m, and an accuracy of 5 mm per 10 m.

Low-cost documentation using smartphones and, where necessary, additional devices is emerging as a new technology. Today, there are several applications for creating 3D models. They differ in performance, possible uses, and, above all, data capacity and export of results. Pix4D catch, RealityScan, and 3DSurvey were used in researching the possibilities.

The tested technologies were tried out in the U Pincû adit, the Johannes mine, and in Kutná Hora city. Generally applicable outputs were also tested, especially visualization options, which are essential for most visitors.

4. Data processing and results

The so-called Wolf Pits was processed as a 3D model by joining of both TLS and drone measurements. There were no problems here, but the technologies used took a whole day of measurement, and further processing was laborious and required another three days of work. Accuracy does not play a major role here; the focus is on determining the shape of the entire work and creating a complete model. Holes in the model were found and filled in using Geomagic Wrap software (Figures 8–9).

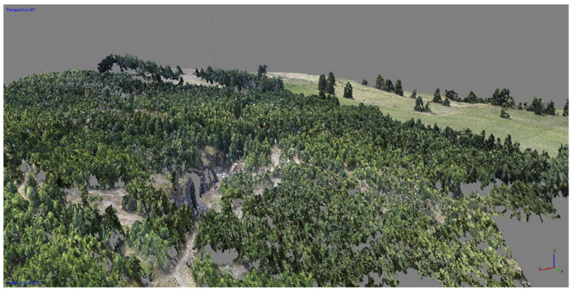


Figure 8. Mesh model from done

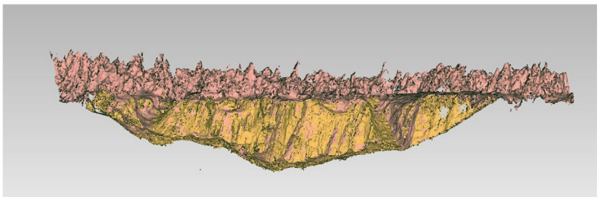


Figure 9. Joined model from drone and TLS

The project East Abertamy was processed by laser data only. The PLS GeoSlam was used and next the ALS technology.

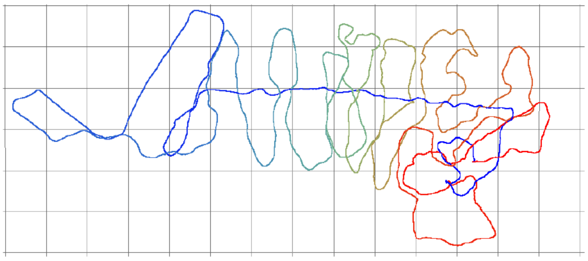


Figure 10. Trajectory in forested area, Eastern Abertamy region, open pits

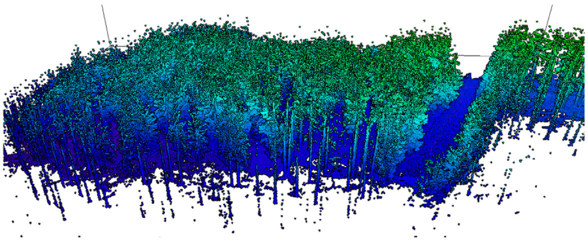


Figure 11. Mesh model Eastern Abertamy region, open pits

Figure 12. ALS data, Czech state DMR5G model, Eastern Abertamy region, open pits from medieval time (tin mining) and the big deposit from sixties of last century (uranium mining)

Walking around the forest site is not easy. It is necessary to estimate the trajectory in advance. More modern devices show the trajectory directly (Faro Orbis), but here we used the older PLS GeoSlam Go, where this task is complicated, the trajectory is not visible, and it is necessary to rely on experience. Even so, it is not possible to maintain a regular trajectory in an untidy forest (Figures 10–11). Furthermore, ALS data from the Czech Republic's state system (DMR5G) was used. This is free data from a shaded raster relief of the 5th generation with a density of 1–2 points per square meter.

In the forest, it is up to an order of magnitude less, and smaller artifacts disappear. However, the model is of high quality and cleared of vegetation. We also used DMR from a low-cost system on an ultralight; the data was an order of magnitude denser, but its quality was not entirely satisfactory (Figures 12–13).

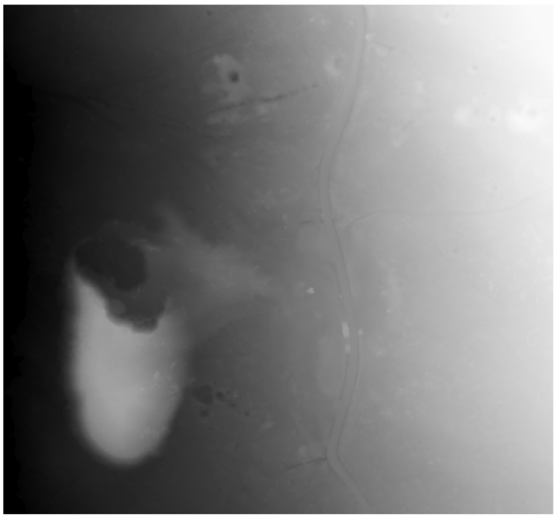


Figure 13. ALS data DMR from Low-cost ALS data

The use of photogrammetry is possible, but the problem is mainly suitable and sufficient lighting and the type of object (Figure 14). Narrow adits cannot be documented in this way.

Figure 14. Photogrammetry in a small, enclosed section of the Kohlreuter mine, Agisoft Metashape software

Photogrammetrical model from Kohlreuter mine can be find o the laboratory web: (https://lfgm.fsv.cvut.cz/projects_mines.html#).

4.1. Johannes mine

In this project, PLS´s were used, GeoSlam go, GeoSlam Horizons and newly Faro Orbis in the last year. Processing is automatic and results in a point cloud. With Faro Orbis, only parts could be textured due to poor lighting (Figure 15).

A short video was created as a demonstration, but the texture is artificial. An effort was also made to create a VR application, which proved to be very laborious, and the results are not yet entirely satisfactory; they are still awaiting publication.

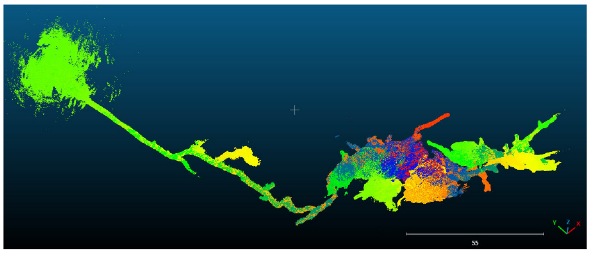


Figure 15. Johanes mine 3D model from PLS

A sample presentation can be found on the laboratory's website in the form of a video, but the texture is missing, which is artificial: (https://lfgm.fsv.cvut.cz/projects_mines.html#)

4.2. Kutna Hora, Barbora adit

Here GeoSlam go and Faro Orbis were used. Once again, point clouds were created, without texture, due to the very difficult conditions (Figures 16–17). However, the data is very valuable for experts and researchers, as only basic documentation techniques such as compasses and measuring tapes have been used to date.

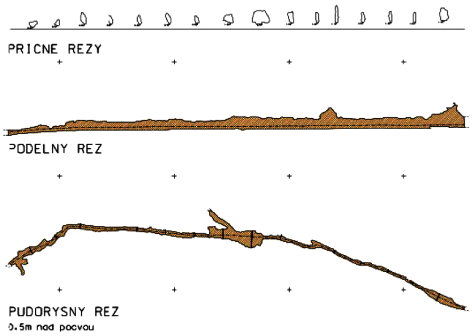


Figure 16. An example of outputs from PLS measurement, cross-sections

Figure 17. Measurement with PLS is very difficult, confined spaces, running water, dampness, and darkness

4.3. „U Pinců“ adit

This small private tunnel was the best documented. It is relatively short, about 50 m, and the outputs from student teaching were used here. TLS BLK360, Trimble X7, Pls Faro Orbis, PLS GeoSlam go, Pix4D and Reality Scan applications were used (Tables 1–2).

Point clouds and textured models were also created here, mainly from smartphone applications. Lighting dark objects remained a persistent problem. A total of five headlamps were used on the operator’s head for smartphone applications, but even so, the results were not ideal.

It is possible to visit the output from Faro Orbis on the YouTube. The video was created using 3DSurvey software: (https://www.youtube.com/watch?v=4UlMgzUFAB4&t=6s)

Table 1. Results of documentation methods in the adit „U Pinců“. Trimble X7 was used as a reference method (most precise)

Device (Method)	RMSE 2D	RMSE 3D	Time of measurement
Trimble X7	–	–	60 min
Leica BLK360	13 cm	14 cm	70 min
iPhone LiDAR	5 cm	23 cm	15 min, but not all space
GeoSlam Go	30 cm	30cm	10 min
Faro Orbis	5cm	5cm	10 min
Reality Scan	–	–	Only small parts

Table 2. Usability of technologies for historical underground irregular spaces

Device (Method)	plus	minus
Trimble X7	Best precision	Too big for small and narrow spaces, problems with light for the in-build camera
Leica BLK360	Precision, small, light tripod	problems with light for the in-build camera
iPhone LiDAR	Low-cost small device	Not usable for large objects, problems with light
GeoSlam Go	Very good and fast, small data amount, small device, but cabled with a data logger	Missing camera, small point density, but ideal for basic documentation
Faro Orbis	Precise, fast, with camera, big data amount	Problems with the camera in dark spaces
Reality Scan	Low-cost, small device	Not usable in this spaces, limited images in free version (250)

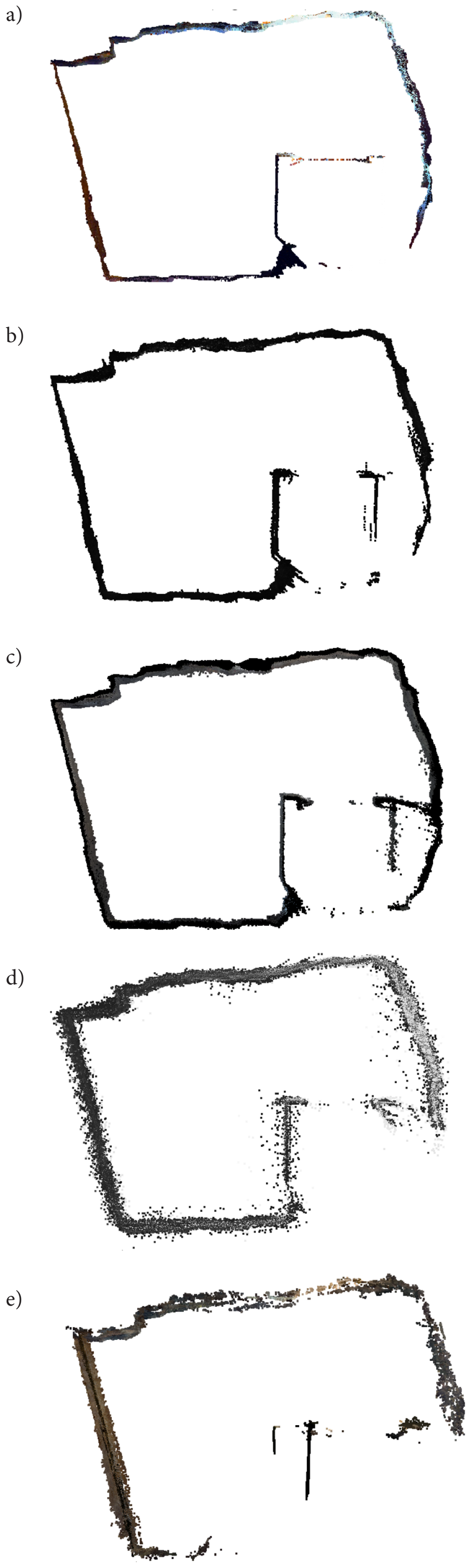


Figure 18. Example of one profile from the captured point clouds: a) Trimble X7; b) Leica BLK360; c) Faro Orbis; d) GeoSlam Go; e) Pix4D Catch

On the Figure 18 a–e cross-sections are shown for comparing of technological outputs. The accuracy and completeness of the cut is determined by the technology used. The most accurate, with minimal data noise, is the Trimble X7 device (Figure 18 a).

5. Discussion

However, TLS works using the stop-and-go method and takes a long time, especially in irregular and narrow underground spaces. With a few exceptions, TLS devices are also larger, mounted on a tripod, and in this case difficult to work with. The exception is the small TLS BLK360, which is not designed for dark and damp spaces. Small PLS devices are therefore ideal, as documentation is carried out on foot, and it is possible to crawling in low spaces and selecting small, shaded areas. This is a huge advantage, as measuring in such difficult terrain is easier after all. However, high humidity is often an obstacle again, and with more modern PLS with cameras, the spaces need to be illuminated. GeoSlam go without a camera and Faro Orbis with a camera were used.

An additional light source screwed directly above the camera has proven to be effective, but larger spaces need to be illuminated with additional powerful light (Figure 19).

Figure 19. Additional light attached to Faro Orbis

Even so, there is still a big problem with texturing dark underground spaces. In most cases, it is not possible to define the texture with sufficient quality, so it is possible to use a model without texture (usually just rock) or even texture surfaces using artificial texture with AI.

In Kutna Hora, Barbora adit, the measurement was very difficult. Based on very narrow spaces and water, high humidity it was necessary to make a service of both instruments after the measurements. Due to the difficulty of the measurements, the results were not entirely ideal. The measurements were always taken back and forth, i.e., as a closed polygon. The measurements had to be repeated several times because the devices reported errors (Figure 20). Even so, the collected data had to be edited manually. GeSlam Go had major problems due to the smaller number of points; on the way there and back, the model split or broke. Therefore, several measurements had to be discarded.

Low-cost technology can only be used for small areas. Pix4Dcatch, based on the iPhone 12 Pro with LiDAR sensor, works well, but in long corridors or tunnels, there are problems with connecting data when walking back and forth. It can be used, but the problem is, logically, with the lighting of the object. Reality Scan has a limited number of images (250) in the free version, and this number is only for a small part of the objects, so this application cannot be recommended. The resulting model was not usable.

From the perspective of technological applicability in historic mines where high precision is not required, a small handheld mobile laser scanner such as the GeoSlam (or similar) appears to be the best option (Figure 21).

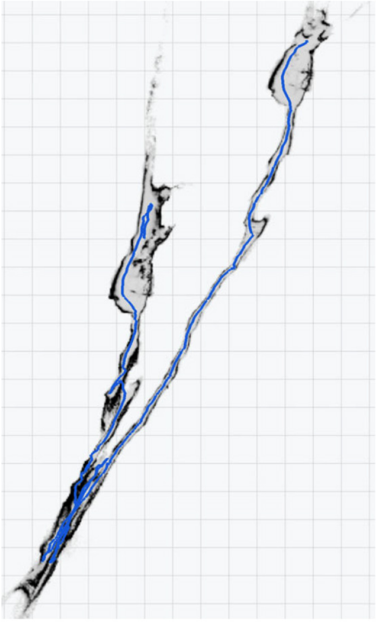


Figure 20. Duplication and data mismatch during back-and-forth transmission, Faro Orbis

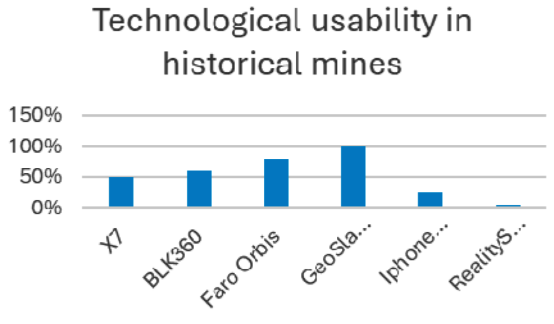


Figure 21. Technological usability of used methods in underground historical mines

6. Conclusions

Based on long-term work with geomatics technologies in historical underground sites, the following conclusions can be drawn:

A) Absolute accuracy

Absolute accuracy denotes the degree of concordance between the reconstructed spatial geometry of an underground excavation and its true position within a georeferenced coordinate framework. For engineering-geological or stability assessments, centimetric positional fidelity is essential when integrating the dataset with digital elevation models, structural-geological interpretations, or geotechnical monitoring records. Methods with inadequate georeferencing stability may introduce systematic displacements that undermine subsequent spatial analyses.

B) Relative accuracy

Relative accuracy concerns local geometric fidelity and the internal coherence of the point cloud or 3D mesh. In the context of mining heritage documentation, this includes precise capture of excavation profiles, deformation patterns, pick-marks, lithological contacts, or support structures. For geomatics, relative accuracy is central to modelling high-resolution, scale-independent geometries used in structural mapping or morphological analyses.

C) Time efficiency

Time efficiency encompasses the duration of in-situ data acquisition, the complexity of data fusion and registration workflows, and the computational costs of generating metrically reliable 3D models. Underground environments often impose restricted access, limited time windows due to ventilation requirements, and safety constraints associated with rockfall or poor ground conditions. Therefore, the temporal performance of the method significantly affects its feasibility for large-scale or multi-epoch documentation campaigns.

D) Response to complex tunnel geometry

Irregular excavation geometries – such as curved workings, variable cross-sections, branching networks, or abrupt directional changes – challenge certain optical and lidar-based techniques. From a geomatics perspective, constrained sightlines reduce point density and affect SLAM stability; from a mining-engineering viewpoint, such geometries often correspond to structurally controlled excavation zones where accurate mapping is crucial.

E) Suitability for variable tunnel dimensions

Historic mine workings commonly feature narrow stope remnants, low adits, or hand-hewn passages. The physical portability of scanning equipment and its ability to operate within tight clearances are therefore critical. In heritage-science applications, accessibility constraints often determine whether delicate or hazardous voids can be documented without intrusive intervention.

F) Environmental resistance

Subsurface environments are characterized by high humidity, dripping water, dust, mud, and low-illumination conditions. These can reduce sensor performance, degrade texture quality, or cause measurement noise. Robustness against moisture ingress, particulate interference, and thermal instability is essential for the reliable operation of both active and passive sensing systems.

G) Capability to record inaccessible volumes

Many underground features – stopes, winzes, raises, collapsed segments, or chimney-like voids – cannot be accessed by personnel for safety or dimensional reasons. Techniques capable of remote sensing, such as tripod-mounted lidar, handheld SLAM-based scanners, or robotic carriers (e.g., UAVs or crawler platforms), offer enhanced coverage of high-risk or structurally unstable areas.

H) Completeness and analytical value of 3D documentation

The final evaluation criterion concerns point-cloud density, spatial coverage, surface continuity, and the ability to derive analytical products such as ortho projections, structural lineaments, volumetric analyses, or deformation monitoring datasets. In heritage science, completeness is essential for conservation planning, while in mining engineering the geometric integrity of the dataset feeds into risk modelling and rock-mechanical assessments.

For the future work, after processing all the data, we would like to place some of the outputs in a virtual museum, which is a long-term student project at the Photogrammetry Laboratory of the Department of Geomatics at the Faculty of Civil Engineering of the Czech Technical University in Prague.

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